U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

RIC 2011

Weld Residual Stress Analysis Validation

Introduction and Motivation

In pressurized-water reactor coolant systems, nickel-based dissimilar metal (DM) welds are typically used to join carbon steel components, including the reactor pressure vessel, steam generators, and the pressurizer, to stainless steel piping. Figures 1 and 2 show a representative nozzle-to-piping connection cross-section, including the DM weld. The DM weld is fabricated by sequentially depositing weld beads as high-temperature molten metal that cools, solidifies, and contracts, retaining stresses that approach or, potentially, exceed the material's yield strength. These DM welds are susceptible to primary water stress-corrosion cracking (PWSCC) as an active degradation mechanism that has led to reactor coolant system pressure boundary leakage. Weld residual stresses (WRS) can be the dominant mechanical driving force for crack initiation and propagation within the DM weld material. Hence, proper assessment of these stresses is essential to accurately predict PWSCC flaw growth and ensure component integrity. Sources of variability in WRS include fabrication, repair, and PWSCC mitigation processes.

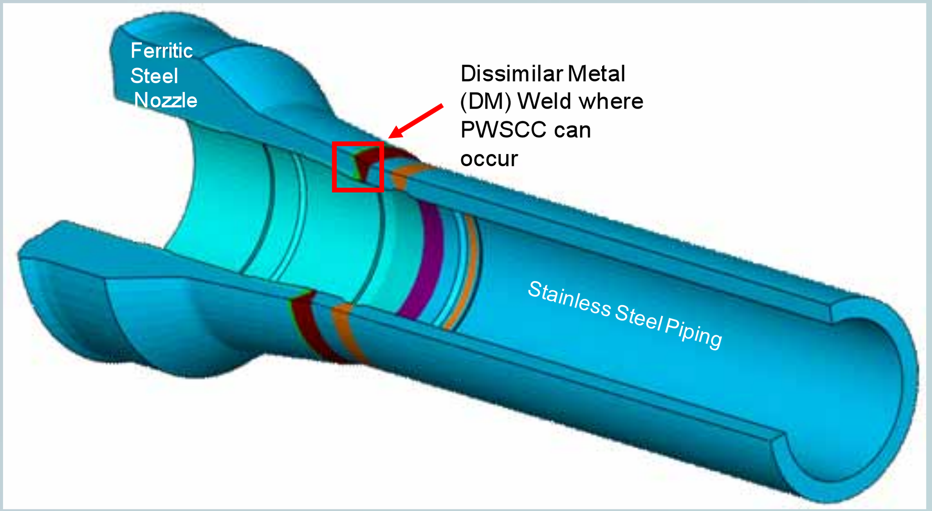

Figure 1. Cutaway view of a carbon steel nozzle DM weld and stainless steel piping typical in a light-water cooled nuclear power plant

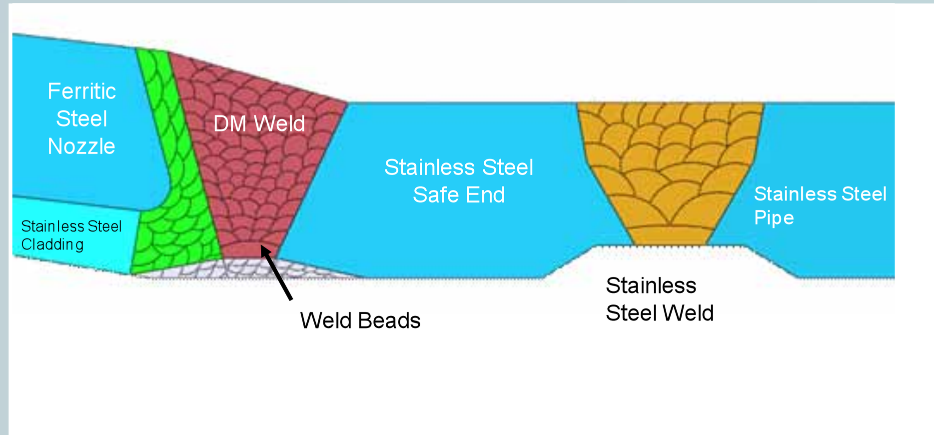

Figure 2. Cross-section of nozzle-to-pipe weld highlighting weld bead pattern

Cooperative Research with EPRI

The U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) signed a memorandum of understanding (MOU) to allow and encourage cooperation in nuclear safety research that benefits both the NRC and industry. This MOU is authorized under Section 31 of the Atomic Energy Act and Section 205 of the Energy Reorganization Act.

The WRS Analysis Validation Project is being conducted under an addendum to the MOU to allow the NRC and EPRI to cooperatively and efficiently perform research on this project.

Objectives for NRC-EPRI Sponsored Research

Support the Office of Nuclear Reactor Regulation (NRR) in developing appropriate WRS/flaw evaluation review guidelines.

Perform independent confirmatory research on industry guidance for performing WRS analysis.

Assess and evaluate the near-term adequacy of industry's mitigation activities where WRS minimization is necessary.

Improve WRS finite element (FE) analysis predictive methodologies.

Assess variability of WRS (mean, scatter, and distribution).

Determine estimates for the uncertainty and distribution of WRS, which are needed in probabilistic analyses (e.g., xLPR Code).

Approach

Develop reasonable assurance that WRS FE models are accurate through a blind validation using well-controlled mockups to various WRS measurement testing techniques.

Phases 1–4 have specific goals and progressively more realistic conditions (Figure 3).

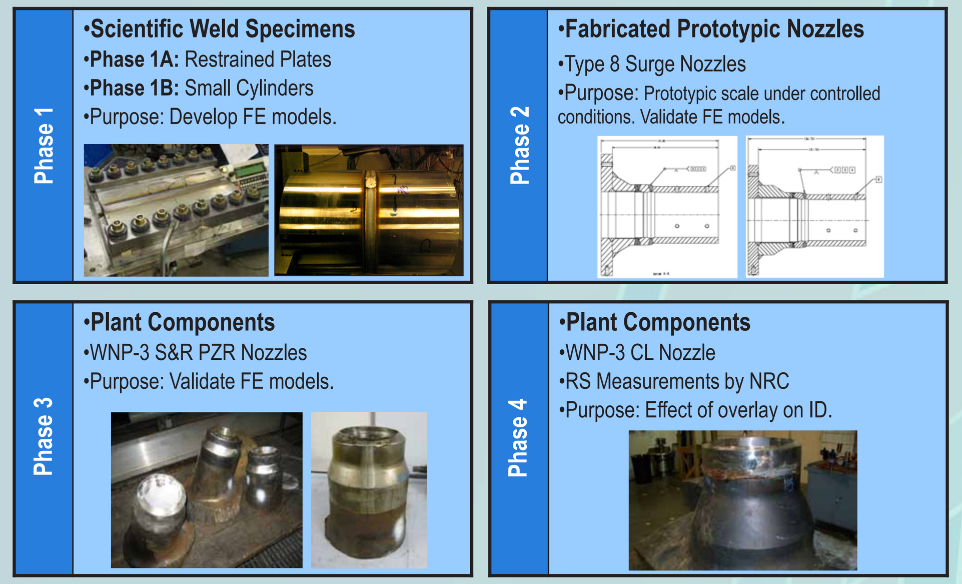

Figure 3. Phases 1 through 4 of the WRS Analysis Validation Program

International WRS Round Robin: Phase 2, Led by NRC Staff

This phase is a double-blind WRS measurement and analysis validation study using a pressurizer surge nozzle geometry. The following international and domestic organizations are participating:

ANSTO (Australia)
AREVA (USA and EU)
Battelle (USA)
Dominion Engineering (USA)
Goldak Technologies (Canada)
ESI Group (USA)
EMC2 (USA)
Inspecta Technology (EU)
Institute of Nuclear Safety System (Japan)
Japan Nuclear Energy Safety Organization
Korea Power Engineering Company
Oak Ridge National Laboratory (USA)
Osaka University (Japan)
Rolls Royce (UK)
Structural Integrity Associates (USA)

FE analysis and measurement results are being kept confidential until all participants have completed their studies. The NRC staff expects to make the measurement results public in early 2011.

WRS Measurement Techniques

Two categories of WRS measurement techniques currently exist:

1. Strain-relief based, in which the stressed material is separated, resulting deformations are measured, and the original residual stresses back-calculated (e.g., deep hole drilling, as shown in Figure 4, incremental hole drilling, contour and slitting techniques);

2. Diffraction based, in which stressed material lattice spacing is measured and compared to representative stress-free material (e.g., neutron diffraction, as shown in Figure 5, and x-ray diffraction techniques).

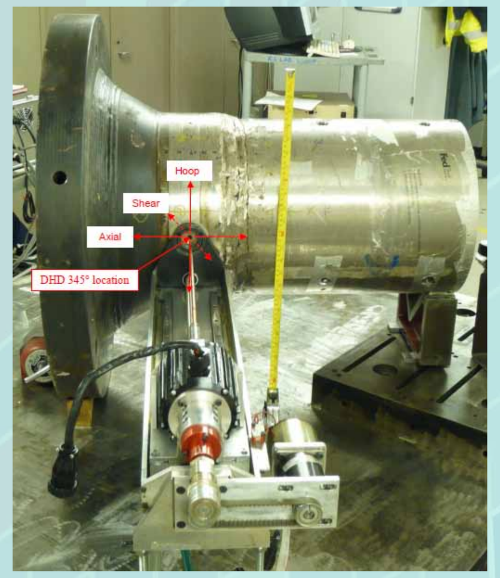

Figure 4. Deep hole drilling technique

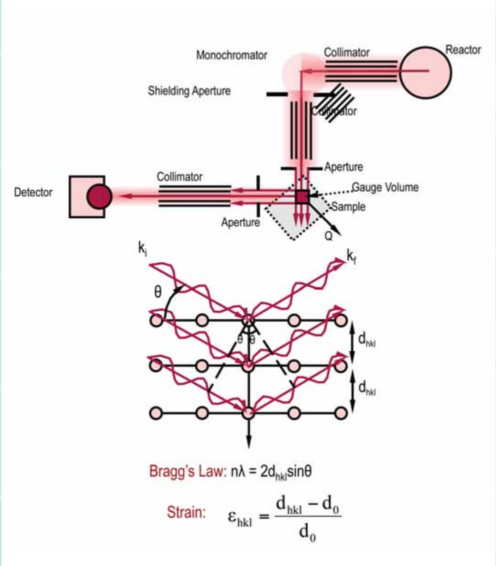

Figure 5. Neutron diffraction concept

Results

The figures below depict typical stress profiles and contours.

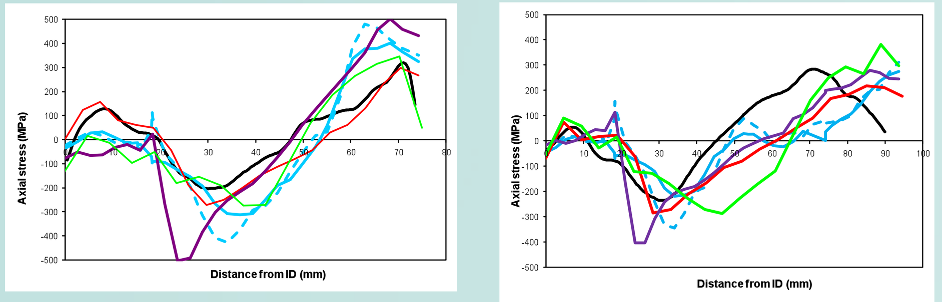

Figure 6. Typical FEA axial stress distributions with deep hole drilling results shown in black

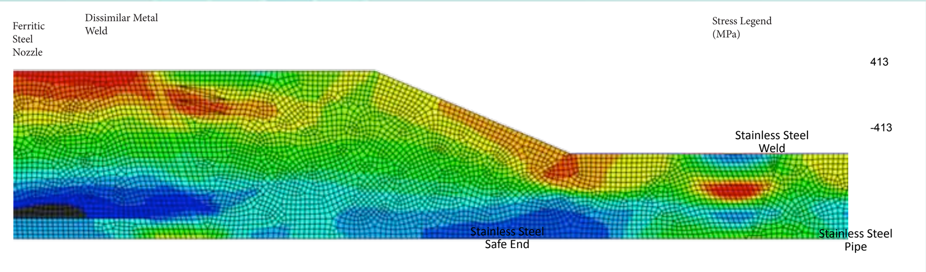

Figure 7. Typical axial stress distribution contour in a nozzle-to-pipe weld configuration

Successes

The WRS Analysis Validation Project has enjoyed the following successes:

- Evaluations of mitigation techniques (MSIP/FSWOL/OWOL/Inlays)
- Provided NRR input to MRP-169 OWOL SER
- Key aspects having the largest impact on WRS analysis results
- Material hardening law (isotropic, kinematic, mixed) and selection of material properties
- Treatment of annealing; note that different FE codes treat this phenomenon differently
- Mechanical property initiation at the time of weld bead deposition—there are significant differences in how FE codes treat this aspect
- Order of weld bead deposition (fabrication sequence) and bead geometry
- Heat input models; it appears that as long as the total amount of heat input is correct then the results will be valid, (i.e., as long as the power is applied over the correct amount of time)
- Validation of modeling technique to measured WRS distributions
- Consistency with inspection results
- Inclusion of stainless steel weld (tends to mitigate ID tensile stresses)
- Repair welds can result in high stress concentrations and should be considered
- Quantification of experimental and numerical uncertainty in WRS values

Additional Information

For more information, contact Dr. Howard J. Rathbun, RES/DE/CIB, at 301-251-7647 or Howard.Rathbun@nrc.gov
Figures 1, 2 and 7 courtesy of Dr. Lee Fredette of Battelle Memorial Institute
Figures 3 and 5 courtesy of John E. Broussard of Dominion Engineering, Inc.
Figure 4 courtesy of Dr. Ed Kingston of Veqter, UK